Composite Structures 251 (2020) 112655

Contents lists available at ScienceDirect

Composite Structures

journal homepage: www.elsevier.com/locate/compstruct

Research Article

Experimental investigation of the crashworthiness performance of fiber and fiber steel-reinforced composites tubes

Samer Gowid [a,*], Elsadig Mahdi [a], Jamil Renno [a], Sadok Sassi [a], Ghais Kharmanda [b], Abdallah Shokry [c]

[a] Department of Mechanical and Industrial Engineering, Qatar University, Qatar
[b] Mechanics Laboratory of Normandy, INSA Rouen, France
[c] Department of Mechanical Engineering, Fayoum University, Egypt

ARTICLE INFO

Keywords:
Composite structure
Composite material
Crashworthiness
Compression test
Sandwich structured composite

ABSTRACT

Crashworthiness plays a key role in energy absorption and hence in vehicle accidents. The energy absorption capacity of laminated composite materials is heavily investigated in the industry due to their low cost, corrosion resistance, and high strength to weight ratio. Thus, this paper experimentally investigates the effect of the addition of woven fiber laminates and fiber steel sandwich laminates on the strength and energy absorption capacity of PVC polymer tubes. The sandwich-structured composite is formed from two glass-fiber composite layers with a steel layer in between. Four normal and hybrid reinforcement configurations are proposed, evaluated, and compared to the benchmark unreinforced tube. The crashworthiness characteristics of the reinforced composite tubes were identified using quasi-static axial compression tests. The crushing parameters, in terms of load–displacement response, load-carrying capacity, Specific Energy (SE) absorption capability, and Crush Force Efficiency (CFE) were determined for each sample. Moreover, Scanning Electron Microscope (SEM) analysis was carried out to investigate the microstructures, which clearly indicate the fractured surfaces. The results show that the tube reinforced with a 1 mm steel layer sandwiched between 2 layers and 4 layers of woven glass-fiber has the highest SE and CFE of 14 J/g and 0.91, respectively, while the tube reinforced with 7 layers of glass fiber layers only has the highest Initial Peak Load (IPF) of 139.36 kN.

1. Introduction

In vehicle accidents, the dissipation of crash forces is of high importance to save lives and protect assets. Composite materials are utilized in various engineering applications due to their excellent weight to strength ratio, low cost, lightweight, corrosion resistance, and environmentally friendly [1]. Sandwich composite materials can replace metals in various applications due to their good characteristics, and thus, several research articles have investigated the combination of steel or aluminum with the glass fiber reinforced epoxy composite. However, the main drawback of composite materials is its complex fabrication processes [2]. The use of composite materials to eliminate the effect of welding on steel beams and the investigation of the crushing behavior of various composite structures yielded improved strength, load carrying capacity and energy absorption capability [1,3,4].

Fiber composite materials have high strength and stiffness, corrosion resistance, in addition to, excellent fatigue characteristics. On the other hand, metals have high bearing strength, impact resistance, and are easy to manufacture and repair. The combination of fibers and metals has the potential to overcome the drawbacks of each other. Fiber metal composite materials combine the merits of both fiber-reinforced composite and metallic materials. Thus, a hybrid composite material would result in having a material with good fatigue, corrosion resistance, high bearing pressure, impact resistance, and good reparability [5–7]. These materials can be manufactured by bonding composite plies to metal plies [8]. Many articles demonstrated that hybrid composite materials possess better mechanical properties and impact resistance characteristics than fiber-reinforced composite materials [9]. Glass-Reinforced Aluminum Laminate GLARE is a material made of alternating layers of thin composite layers and thin metal sheets. The high carbon fiber stiffness provides more efficient crack resistance. Also, the existence of an Aluminum layer leads to an improved resistance, which makes GLARE favorable for the structures of robots, aircraft, spaces, tubes, and drive shafts [10]. The mechanical behavior and the fracture modes of fiber-reinforced metal laminates (FRMLs) have been studied and the results of these studies proved the

* Corresponding author.
E-mail address: samer@qu.edu.qa (S. Gowid).

https://doi.org/10.1016/j.compstruct.2020.112655
Received 17 June 2020; Accepted 18 June 2020
Available online 29 June 2020

superiority of FRMLs over fiber reinforcement materials [11,12]. For example, Carbon fiber Aluminum hybrid sandwich composite plates yield high specific energy of 89 kJ/kg on average [13]. A number of methods and techniques are used to model the highly nonlinear behavior of composite materials including artificial intelligence [14,15].

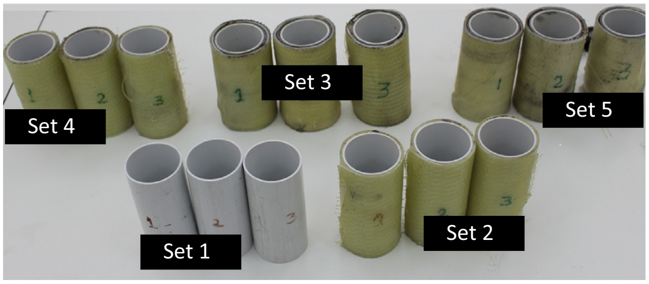

Fig. 1. 5 sets of testing specimens.

The hybridization of fiber metal layers gained the attention of structural crashworthiness in the composite materials industry. Due to the importance of tubes, some articles investigated the fiber and hybrid fiber metal reinforcements of composite tubes. The energy absorption characteristics of different composite tubes were evaluated in [16]. The results proved the good crashworthiness performance of the fiber and fiber metal reinforced composite tubes [16,17]. Thus, this paper investigates the behavior and crashworthiness performance of multiple fiber and fiber metal reinforcement configurations with the objective to identify the best performing configuration. This is achieved by exploring different reinforcement configurations, including glass fiber/steel hybrid reinforcement configurations, and then identifying the configuration with the best crashworthiness

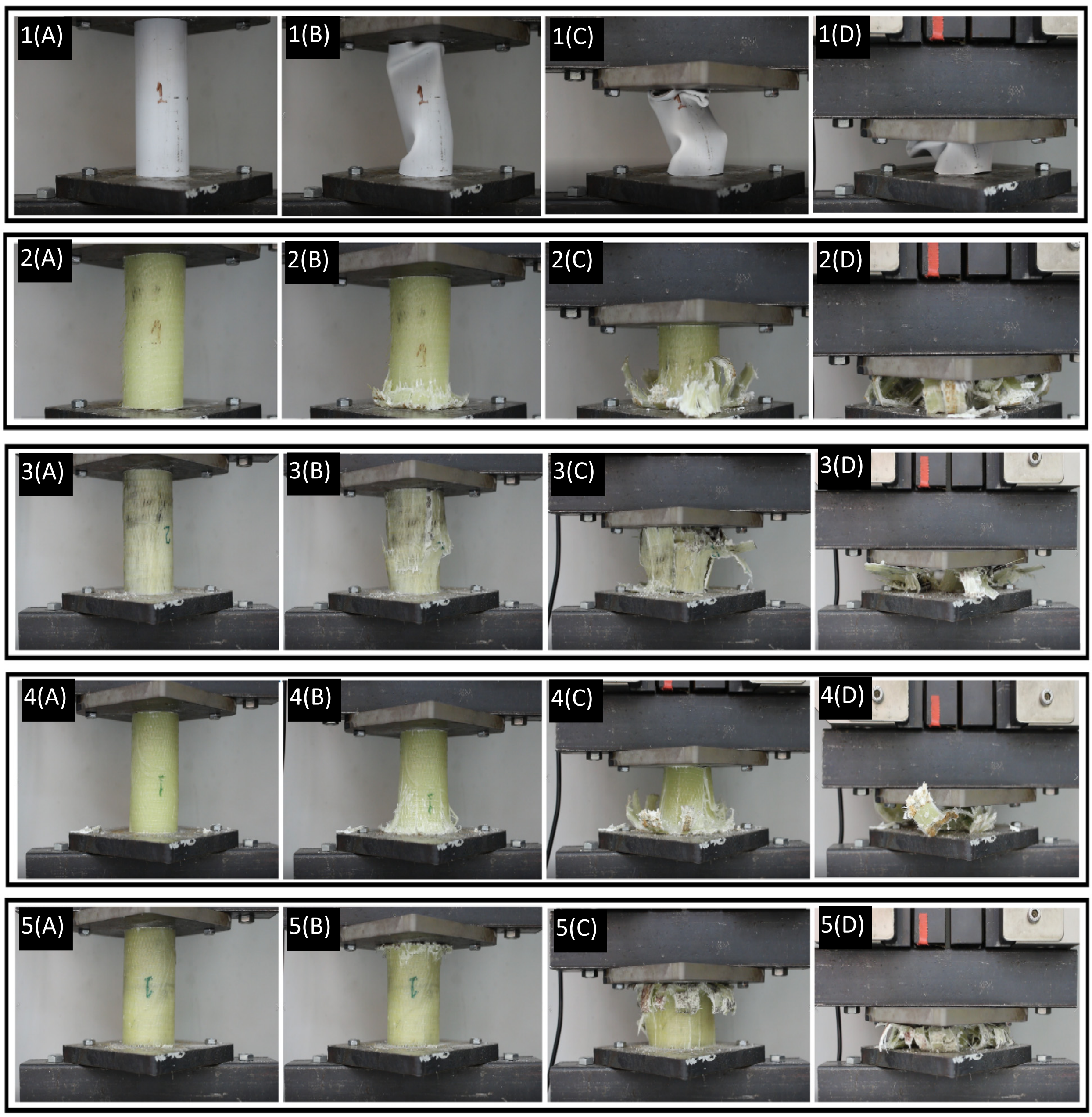

Fig. 2. Polymer, fiber, and fiber metal laminated composite tubes under crush loading ((A) at time 0 s; (B) after 10 s, (C) after 30 s, and (D) after 50 s).

performance and specific energy absorption capability. The fractured surfaces are analyzed using the Scanning Electron Microscope (SEM).

2. Methodology

2.1. Materials and testing

Five sets of tubes; non-reinforced tubes (set1), and four differently reinforcement tubes (sets 2–5), were manufactured and then tested with a view to identifying the best performing configuration/type. The reinforcement configurations are as follow: (a) 5 layers of woven glass fiber (set 2), (b) 1 mm steel layer sandwiched between two lower layers and two upper layers of woven glass fiber (set 3), (c) 7 layers of woven glass fiber (set 4), (d) 1 mm steel layer sandwiched between 2 lower layers and 4 upper layers of woven glass fiber (set 5). The average unit weights of the configurations a, b, c and d are 118, 203, 149, 235 grams, respectively, while the weight of the PVC tube is 45 grams. The dimensions of all tubes in all sets are 50 mm outer diameter, 2 mm wall thickness and 100 mm length. A set of three specimens from each configuration/type were tested (see Fig. 1).Fig. 2.

The reinforcement layers are made of woven glass fiber and epoxy resin. The woven glass fiber material consists of unidirectional fibers wrapped in the longitudinal direction of the tubes and glued together using an epoxy resin by hand lay-up method [18]. Table 1 presents the technical specifications of the glass fiber-reinforced epoxy material used for reinforcement [19].

Table 1
Technical specifications of the glass-reinforced epoxy composite material [19].

Parameter	Value
Ultimate strength	330 MPa
Flexural strength	270 MPa
Modulus of elasticity (E)	3.294 GPA
Fiber to resin ratio (W_f)	≈50%
Lay-up Sequence	unidirectional 0° plain weave

The INSTRON tensile testing machine was adjusted to carry out quasi-static compression tests at a constant compression speed of 100 mm/min. The length of the test specimens is 100 mm.

3. Results and discussion

The behavior of composite and sandwiched structured composite is complicated due to the complex, and highly anisotropic behavior of heterogeneous materials. This section illustrates the collapsing mechanics, failure modes, and crushing behavior, and evaluates the crushing performance of several glass-fiber and glass-fiber metal reinforced composite tubes (see Section 2.1) under in-plane compressive loading conditions.

3.1. Collapsing mechanism

Figure 2 shows samples of the collapsing mechanisms of the 5 reinforcement configurations addressed in this paper. The collapsing mechanism of the unreinforced polymer benchmark tube is shown in Figure 2(1), while the photos 1(A), 1(B), 1(C) and 1(D) show the progression of failures at 0, 10, 30 and 50 s, respectively. Figure 2(2) illustrates the collapsing mechanism of the second configuration, which is a polymer tube reinforced with 5 layers of glass-fiber epoxy composite, while photos 2(A), 2(B), 2(C) and 2(D) show the progression of failure at 0, 10, 30 and 50 s, respectively. Likewise, photos 3(A–D), 4(A–D) and 5(A–D) depict the collapsing mechanism of a PVC tube reinforced with 1 mm steel layer sandwiched between two lower layers and two upper layers of woven glass fiber, 7 layers of woven glass fiber, and 1 mm steel layer sandwiched between 2 lower layers and 4 upper layers of woven glass fiber, respectively. It can be observed that the PVC tube, shown in Figure 2(1)(1A–1D), was failed due to buckling. Photos

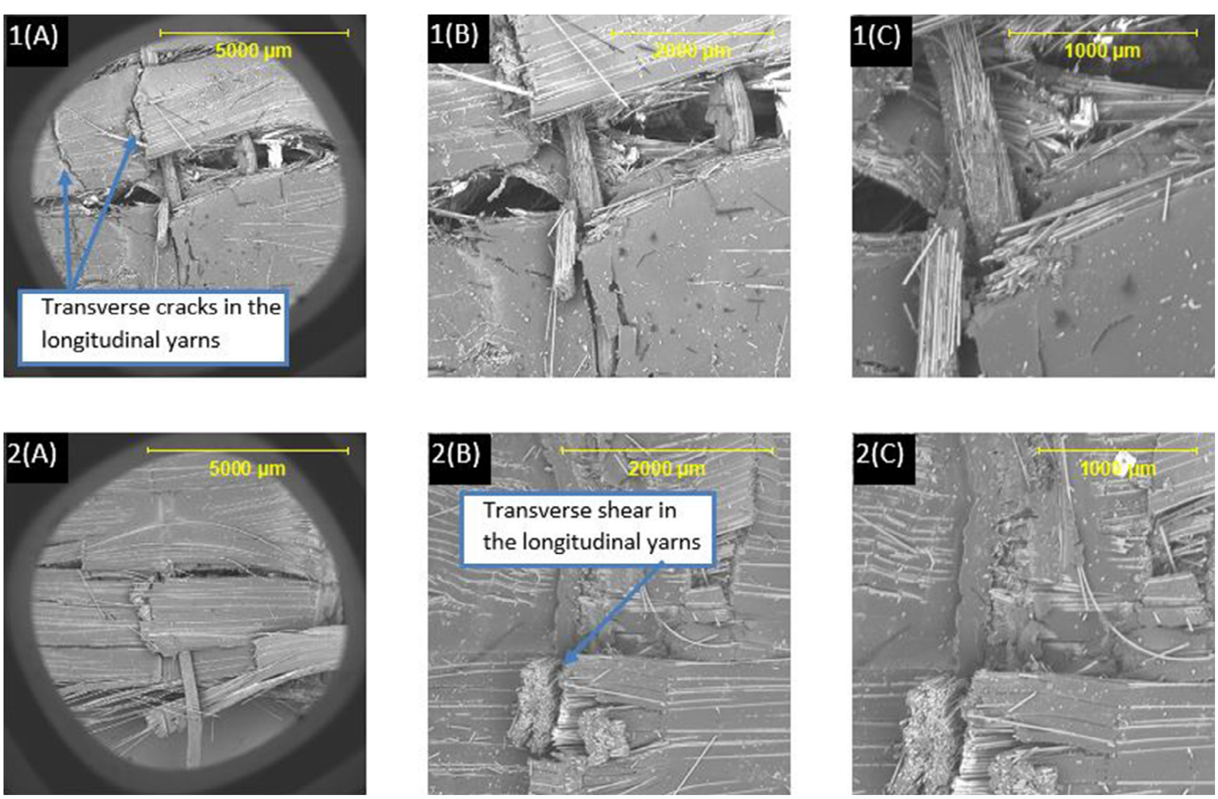

Fig. 3. Optical micrographs of sections through the crush zones of the 7 glass fiber layers (1(A)) and the 7 glass fiber metal layers (2(A)) reinforced composite tubes.

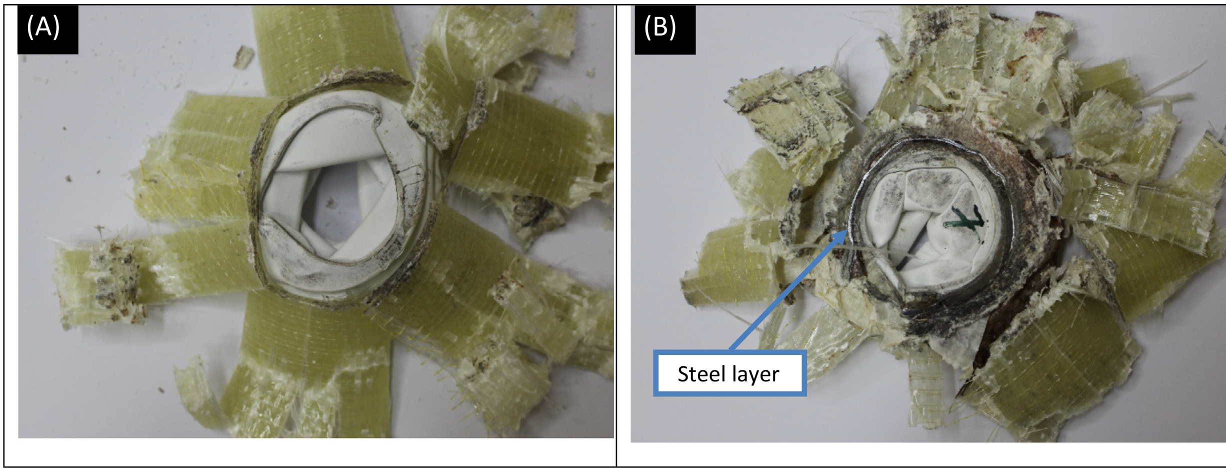

Fig. 4. Crushed 7 glass fiber layers (photo A) and 7 glass fiber metal layers (photo B) reinforced composite tubes (10 mm height).

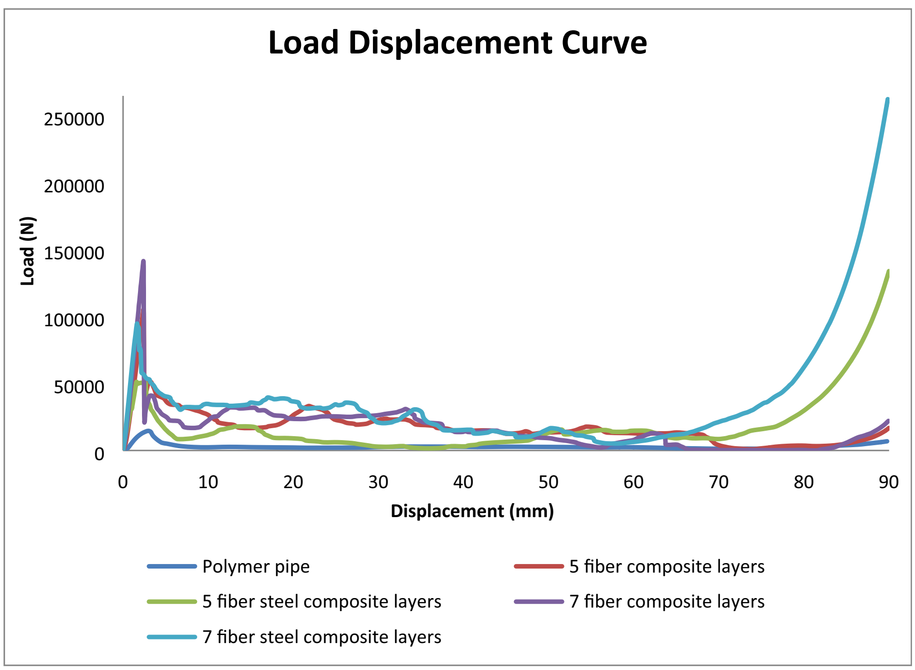

Fig. 5. Load displacement behavior of the addressed tube reinforcement configurations.

2(B) and 4(B)) illustrate that the failure was initiated in the form of cracks at the lower end of the glass fiber reinforced tubes, while the failure was initiated at the upper end and the middle of the tube for the specimens reinforced with fiber and steel layers (hybrid reinforcement). The middle part of the fiber steel-reinforced tube was subject to longitudinal and transverse shearing.

3.2. Failure modes

Farley and Jones [12] investigated the crush behavior of fiber-reinforced composite tubes and summarized that the crush response can be categorized into three modes; namely (a) transverse shearing, (b) lamina bending and (c) local bulking. For brittle fiber reinforced tubes, the transverse shearing crushing mode takes place when the lengths of the longitudinal and interlaminar cracks are less than the laminate thickness. On the contrary, the lamina binding crushing mode takes place when the length of the interlaminar and intralaminar cracks is very long (> 10 times the laminate thickNess) and parallel to the fibers. In the case of brittle fracturing crush mode, the length of the interlaminar cracks varies between one and ten times the thickness of the laminate. The reinforced tubes investigated in this paper failed by long longitudinal and transverse cracks, lamina bending, and splaying, in which delamination caused plies to bend resulting in transverse shear failures or axial splitting and bending took place. Thus, the major failure modes that took place are transverse shearing and lamina bending.

For the best performing reinforcement configurations, as shown in Fig. 3, photos 1(A–C) illustrates the failure modes in the 7 glass fiber layers reinforced composite tube, while photos 2(A–C) illustrate the failure modes in the 7 glass fiber steel layers reinforced composite tube. The photos of the crushed specimens of the best performing reinforcement configurations are shown in Fig. 4. It can be observed that the failure in the outer fiber composite layers as well as the deformation profile of the PVC tube are different.

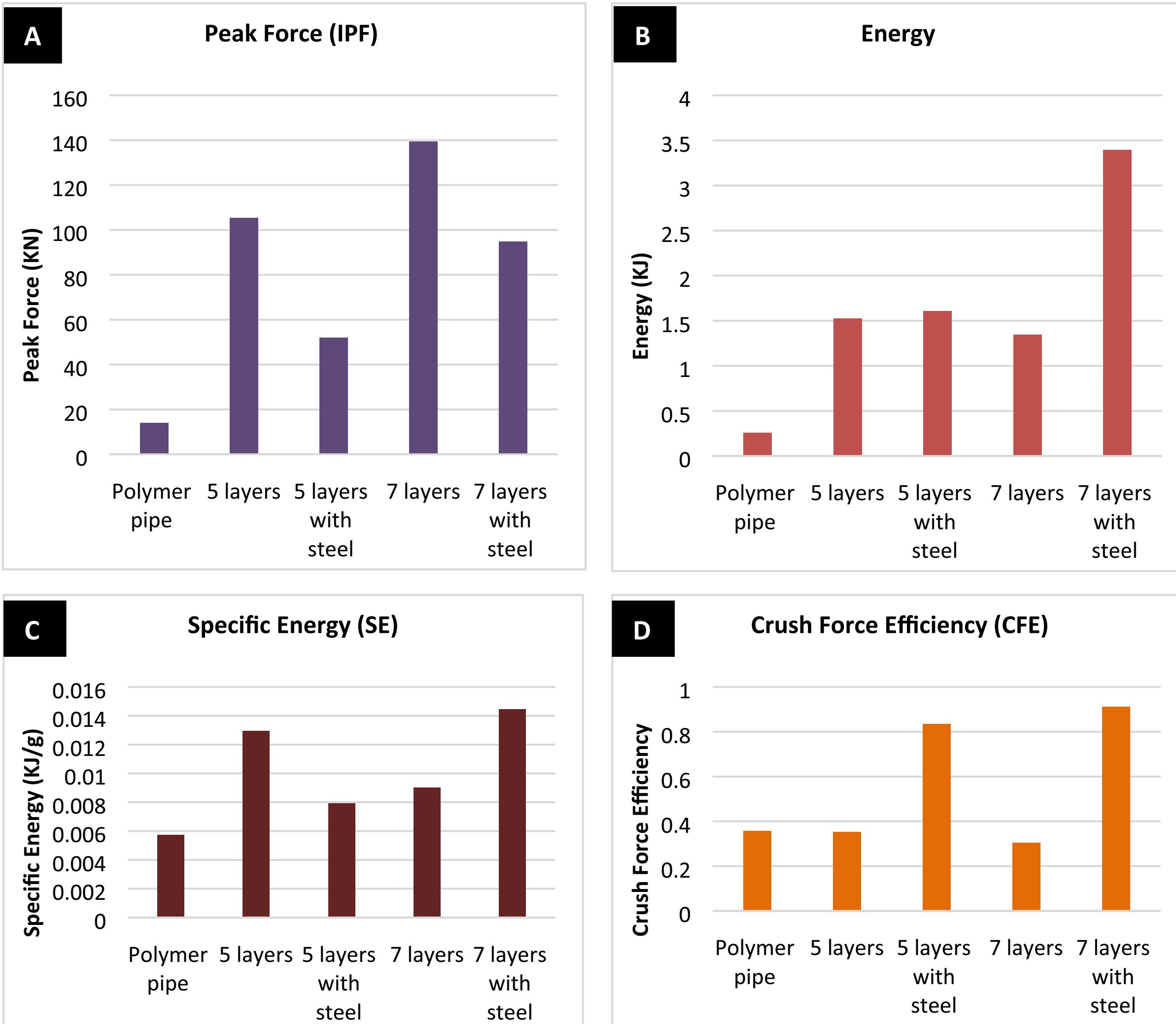

Fig. 6. Bar charts summarizing the crushing performance parameters (chart A: Initial peak force, chart B: Energy absorption, chart C: Specific energy and chart D: Crush force efficiency).

3.3. Load displacement behavior and crashworthiness performance

Fig. 5 shows the load–displacement behavior of the addressed tube reinforcement configurations from 0 to 90 mm displacement, giving that the total length of the specimens is 100 mm. It can be observed that the tube reinforced with 7 glass fiber layers has the maximum initial first force with an IPF value of 139.36 kN, while the unreinforced tube has the lowest IPF (13.99 kN). The tube reinforced with 7 layers of glass fiber and steel (hybrid reinforcement) outperformed the other reinforcement configurations in terms of crush force efficiency with a CFE value of 0.91. The fiber-steel reinforced composite tubes have a noticeable increase in the load-carrying capacity in the following displacement range 70 mm to 90 mm. This is due to the existence of the steel material that significantly increases the stiffness of the crushed composite tube at these displacement values (70 mm to 90 mm), as shown in Fig. 4.

Crashworthiness performance parameters; namely Initial Peak Force (IPF), Energy (E), Specific Energy (SE), and Crush Force Efficiency (CFE), are identified and graphically represented in Fig. 6; charts A–D, respectively. For the IPF parameter, the 7 glass fiber layers reinforced composite tube outperformed the other reinforcement configurations in terms of IPF with an IPF value of 139.36 kN compared to 13.99 kN for the benchmark configuration (unreinforced polymer tube). The composite tube reinforced with 7 fiber-metal layers yielded the highest specific energy and crush force efficiency with a specific energy of 0.01443 kJ/g and a crush force efficiency of 0.91 compared to 0.0057 kJ/g and 0.35 for the benchmark PVC specimens, respectively (see Fig. 6 – charts C & D).

4. Conclusion

This study presents an experimental investigation into the effect of the number of layers and combination of fiber metal laminates on the crushing behavior, load-carrying capacity, crash force efficiency and specific energy of composite reinforced polymer tubes. Four reinforcement configurations with a fifth configuration for the benchmark unreinforced polymer tube are manufactured, tested, evaluated for crashworthiness, and then compared. The four reinforcement configurations are as follow: (a) 5 layers of woven glass fiber (set 2 in Fig. 1), (b) 1 mm steel layer sandwiched between two lower layers and two upper layers of woven glass fiber (set 3 in Fig. 1), (c) 7 layers of woven glass fiber (set 4 in Fig. 1), (d) 1 mm steel layer sandwiched between 2 lower layers and 4 upper layers of woven glass fiber (set 5 in Fig. 1). The tube reinforced with only 7 glass fiber composite layers outperformed the other reinforcement configurations in terms of IPF; with an IPF value of 139.36 kN compared to 13.99 kN for the benchmark configuration (unreinforced PVC tube). The composite tube reinforced with 7 glass fiber-steel composite layers yielded the highest specific energy and crush force efficiency with a specific energy of 0.01443 kJ/g and a crush force efficiency of 0.91 compared to 0.0057 kJ/g and 0.35 for the benchmark specimens, respectively.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] O. Laban, S. Gowid and E. Mahdi, "Experimental Investigation and Uncertainty Prediction of The Load-Carrying Capacity of Composite Double Hat for Lattice Core Sandwich Panels Using Artificial Neural Network," in 2020 IEEE International Conference on Informatics, IoT, and Enabling Technologies (ICIoT), Doha, 2020.
[2] Misri D et al. The effect of winding angles on crushing behavior of filament wound hollow kenaf yarn fibre reinforced unsaturated polyester composites. Fibers Polym 2015;16(10):2266–75.
[3] Al-Abtah F, Mahdi E, Gowid S. The use of composite to eliminate the effect of welding on the bending behavior of metallic pipes. Compos Struct 2020;235 (1):111793.
[4] Laban O, Gowid S, Mahdi E, Musharavati F. Experimental investigation and artificial intelligence- based modeling of the residual impact damage effect on the crashworthiness of braided carbon/kevlar tubes. Compos Struct 2020;243:11247.
[5] R. Alderliesten and R. Benedictus, "Fiber/metal composite technology for future primary aircraft structures," in 48th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference; , Honolulu. Reston, 2007.
[6] S. Gowid, D. R., S. Ghani and A. Shokry, "Robustness Analysis of the FFT-based Segmentation, Feature Selection and Machine Fault Identification Algorithm," Insight - Non-Destructive Testing and Condition Monitoring, vol. 61, no. 5, pp. 271-278, 2019.
[7] Chang P, Yeh P, Yang J. Fatigue crack initiation in hybrid boron/glass/aluminium fiber metal laminates. Mater Sci Eng 2008;496:273–80.
[8] Ogelesang L, Vlot A. Development of fibre metal laminates for advanced aerospace structures. J Mater Process Technol 2000;103(1):1–5.
[9] Chandrasekar M. An experimental review on the mechanical properties and hygrothermal behaviour of fibre metal laminates. J Reinf Plast Compos 2016. https://doi.org/10.1177/0731684416668260.
[10] Tamilarasan U, Karunamoorthy L, Palanikumar K. Mechanical properties evaluation of the carbon fibre reinforced aluminium sandwich composites. Mater Res 2015;18(5). https://doi.org/10.1590/1516-1439.017215.
[11] Afaghi-Khatibi Akbar, Lawcock Glyn, Ye Lin, Mai Yiu-Wing. On the fracture mechanical behaviour of fibre reinforced metal laminates (FRMLs). Comput Methods Appl Mech Eng 2000;185(2-4):173–90. https://doi.org/10.1016/S0045-7825(99)00258-3.
[12] Farley G, Jones R. Crushing characteristics of fiber reinforced composite tubes. J Compos Mater 1992;26:37–50.
[13] Xu J et al. Crashworthiness of carbon fiber hybrid composite tubes molded by filament winding. Compos Struct 2016;139:130–40.
[14] Shokry A, Gowid S, Kharmanda G, Mahdi E. Constitutive models for the prediction of the hot deformation behavior of the 10%Cr Steel Alloy. Materials 2019;12 (18):2873.
[15] Gowid S, Mahdi E, Al-Abtah F. Modeling and Optimization of the crushing behavior and energy absorption of plain weave composite hexagonal quadruple ring systems using artificial neural network. Compos Struct 2019;229:111473.
[16] Hu D. et al.Energy absorption characteristics of composite tubes with different fibers and matrix under axial quasi-static and impact crushing conditions. J Mech Sci Technol 2018;32:2587–99.
[17] Supian A et al. Hybrid reinforced thermoset polymer composite in energy absorption tube application: a review. Defence Technology 2018;14(4):291–305.
[18] Mohamed H, Aly M, Shokry A. Numerical and experimental characterization of composite leaf spring subjected to bending. J Mech Eng Res Dev 2020;43 (2):371–83.
[19] Singh M et al. Determination of strength parameters of glass fibers reinforced composites for engineering applications. Silicon 2019;12:1–11.